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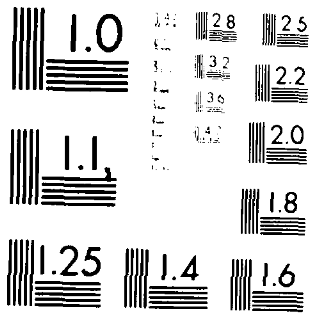

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Part II

AIRCRAFT TRANSPARENCY TESTING METHODOLOGY AND EVALUATION CRITERIA

Part II - Methodology Development for Improved Durability

Kenneth I. Clayton
Blaine S. West

University of Dayton Research Institute
300 College Park Avenue
Dayton, Ohio 45469

April 1983

Final Technical Report for Period January 1982 - February 1983

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FLIGHT DYNAMICS LABORATORY
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Malcolm E Kelley

MALCOLM E. KELLEY
Project Engineer

R. Harley Walker

R. HARLEY WALKER
Group Leader
Subsystems Development Group

FOR THE COMMANDER

SOLOMON R. METRES
Director
Vehicle Equipment Division

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This two-part report defines a methodology and criteria for testing and evaluating the durability of high performance aircraft transparencies through the use of simulated in-service environments. Part I presents and analyzes relevant information/data on applicable operational environments, candidate test methods, and previously used simulation/testing techniques. Appropriate corrective action is recommended to circumvent knowledge voids

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and/or test method deficiencies. A realistic and cost-effective durability evaluation criteria is presented in Part II for monolithic stretched acrylic, coated monolithic polycarbonate, and acrylic faced/polycarbonate laminate configurations.

FOREWORD

The efforts reported herein were performed by the Aerospace Mechanics Division of the University of Dayton Research Institute (UDRI), Dayton, Ohio, under Air Force Contract F33615-81-C-3421. The program was sponsored by the Air Force Wright Aeronautical Laboratories, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. Air Force administration direction and technical support was provided by Mr. Malcolm E. Kelley, AFWAL/FIER, the Air Force Project Engineer, and Mr. R. Harley Walker, AFWAL/FIER.

The work described herein was conducted during the period 18 January 1982 through 18 February 1983. University of Dayton project supervision was provided by Mr. Dale H. Whitford, Supervisor, Aerospace Mechanics Division, and Mr. Blaine S. West, Head, Applied Mechanics Group. Technical effort was accomplished under Messrs. B. S. West and K. I. Clayton as Principal Investigators.

The authors wish to express their appreciation to the ASTM F7.08 committee members, especially those associated with the military aircraft transparency suppliers, for providing helpful contributions and comments relative to the effort reported herein.

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SECTION 1
SCOPE

This report presents a test methodology for evaluating the durability of high performance USAF transparency systems. Section 2 specifies the exposure/tests (coupon, subscale, full scale), with conformance criteria, to be conducted for the following three material configurations: monolithic stretched acrylic, coated polycarbonate, and acrylic faced/polycarbonate laminate. Section 3 describes the techniques to be used in environmentally conditioning the test samples to simulate in-service exposure. Section 4 presents the recommended procedures for conducting non-standard tests. Tables 1, 2, and 3 summarize the test and exposure requirements, along with acceptance criteria, for each of the three transparency material systems under study.

1.1 APPLICABLE DOCUMENTS

MIL-P-25690A, Military Specification-Plastic, Sheets and Parts, Modified Acrylic Base, Monolithic, Crack Propagation Resistant.

ANSI/ASTM F484-77, Standard Test Method for Stress Crazing of Acrylic Plastics in Contact with Liquid or Semi-liquid Compounds.

FTM 406, Method 302, Federal Test Method Standard for luminous transmittance and haze of transparent plastics.

ASTM F736-81, Standard Practice for Impact Resistance of Monolithic Polycarbonate Sheet by Means of a Falling Weight.

ANSI/ASTM F330-79, Standard Method for Bird Impact Testing of Aerospace Transparent Enclosures.

ANSI/ASTM D952-75, Standard Test Method for Bond or Cohesive Strength of Sheet Plastics and Electrical Insulating Materials.

ANSI/ASTM E229-70 (Reapproved 1976), Standard Test Method for Shear Strength and Shear Modulus of Structural Adhesives.

ASTM D3762-79, Standard Test Method for Adhesive/Bonded Surface Durability of Aluminum (Wedge Test).

ANSI/ASTM F521-77, Standard Methods of Testing Transpare Laminates for Bond Integrity.

ANSI/ASTM F520-77, Standard Test Method for Environmental Resistance of Aerospace Transparencies.

MIL-P-83310(USAF), Military Specification-Plastic Sheet, Polycarbonate, Transparent.

MIL-P-8184B, Military Specification-Plastic Sheet, Acrylic, Modified.

TABLE 1

DURABILITY EVALUATION OF HIGH PERFORMANCE USAF TRANSPARENCY SYSTEMS
MONOLITHIC STRETCHED ACRYLIC* SUMMARY

TEST PARAMETER	TEST METHOD	ENVIRONMENTAL CONDITION	SIMULATION	ACCEPTANCE CRITERIA
Surface Chemical Craze	1"x7" beam per MIL-P-25690A, Para. [illegible]; ASTM F 484-77 or equiv.; or 1 x15" incremental stress beam per Sect. 4.1; isopropyl alcohol & ethylene glycol; f=2000 psi	Accelerated weathering	Q.U.V., 120°F, 7 hr. UV/5 hr. condensation cycles; 264 hrs. = 1 equiv. yr.	No crazing after 3 equiv. yrs. of exposure/test.
Haze Transmittance	F406, Method 3022, or equivalent			After 3 equiv. yrs. of exposure/test, haze < 4% and luminous transmittance to be within 2% of unexposed value.
Impact: (a) Coupon	Falling weight plate or beam per ASTM F736-81 or Sect. 4.2 (high rate MTS beam test)	Baseline (unexposed) and accelerated weathering		After 3 equiv. yrs. of exposure/test, threshold-of-failure energy to be within 15% of unexposed value.
(b) Subscale	12"x12" plates, free edge, air cannon tested using 1" dia. steel sphere			After 3 equiv. yrs. of exposure/test, threshold-of-failure energy to be within 15% of unexposed value.
Thermal Shock	In accordance with ASTM F520-77, plus rapid drying in partial vacuum	accelerated weathering	Refer to ASTM F520-77	After 3 equiv. yrs. of exposure/test, no loss of coating, [illegible], spalling, [illegible] or other visible [illegible]
Abrasion Resistance (a) In-flight	3" sq. samples per Sect. 4.3; following QUV and abrasion, measure haze with a std. hazemeter	Accelerated weathering plus salt blast abrasion	(264 hrs. acc. weathering followed by 8 cycles of salt blast) x 1 = 1 equiv. yr, x 2 = 2 equiv. yr, x 3 = 3 equiv. yr.	After exposure/test, haze < 4% after 1 equiv. yr, haze < [illegible] after 2 equiv. yr, haze < 6% after 3 equiv. yr.
(b) Flightline	4"x4" test samples subjected to 50 normal cleanings at 33 hr. intervals	accelerated weathering	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles; 264 hr. = 1 equiv. yr.	After 3 equiv. yrs. of exposure/test, no visible damage and haze < 4%.
Edge Attachment	Flex. beams, approx. 3"x15", simulating design cross-section and edge fixity, per Sect. 4.4; 3- or 4-point loaded at high rate (2000 in/min)	Unexposed	Critical combined load condition during bird impact and/or in-flight	Successful edge design will exceed design ultimate load without failure
Pressure/Temperature/Durability	Full-scale transparency installed in airframe support structure; Bldg. 65 Test Facility at WPAFB	Simulated temp. and press. mission profiles combined with critical ground environment, incorporating realistic rates to evaluate thermal shock.		Successfully withstand [illegible] simulated flight hours and 3 equiv. yrs. of flightline exposure/test
Birdstrike	Full-scale transparency installed in airframe support structure; AEDC test per ASTM F330-79.	Unexposed; following flight/flightline testing in Bldg. 65 facility; and from in-service at yearly intervals	In-flight birdstrike	Pass impact of 4 lb. bird at specified velocity.

*MIL-SPEC Qualified

TABLE 2

DURABILITY EVALUATION OF HIGH PERFORMANCE USAF TRANSPARENCY SYSTEMS
COATED MONOLITHIC POLYCARBONATE* SUMMARY

TEST PARAMETER	TEST METHOD	ENVIRONMENTAL CONDITION	SIMULATION	ACCEPTANCE CRITERIA
Surface/Chemical Craze	1"x7" beam per MIL-P-83310, Para. 4.5.5.2, ASTM F484-77 or equiv.; or 1"x15" incremental stress beam per Sect. 4.1; isopropyl alcohol & ethylene glycol; f=2000 psi.	Accelerated weathering	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles; 264 hrs. = 1 equiv. yr.	No crazing after 3 equiv. yrs. of exposure/test
Haze/Transmittance	FTM 406, Method 3022, or equivalent			After 3 equiv. yrs. of exposure/test, haze < 4% and luminous transmittance to be within 2% of unexposed value.
Coating Adhesion	Rain impingement at 500 mph in a 1-inch/hr. rainfall on rotating arm apparatus at WPAFB.	Accelerated weathering plus stress	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles, 264 hr.=1 equiv. yr. in combination with an outer fiber stress of 1000 psi	After 3 equiv. yrs. of exposure and 5 min. test, no substantial amount of coating removal, measured by S.E.M. exam.
Coating Embrittlement (Impact)	Falling weight beams per ASTM 736-91 or Sect. 4.2 (high rate KTS beam test).	Baseline (unexposed) and accelerated weathering plus stress	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles; 264 hrs. = 1 equiv. yr.	After 3 equiv. yrs. of exposure/test, threshold-of-failure energy to be within 15% of unexposed value.
Thermal Shock	**In accordance with ASTM F520-77, plus rapid drying in partial vacuum**	Accelerated weathering	Refer to ASTM F520-77	After 3 equiv. yrs. of exposure/test, loss of coating, cracking, spalling, loss of transparency, or other visible deterioration.
Abrasion Resistance (a) In-Flight	3" sq. samples per Sect. 4.3; following QUV and abrasion, measure haze with a std. hazemeter.	Accelerated weathering plus salt blast abrasion	(264 hrs. acc. weathering followed by 8 cycles of salt blast) x 1 = 1 equiv. yr, x 2 = 2 equiv. yr, x 3 = 3 equiv. yr.	After exposure/test, haze < 4% after 1 equiv. yr, haze < 5% after 2 equiv. yr. haze < 6% after 3 equiv. yr.
(b) Flightline	4"x4" test samples subjected to 50 normal cleanings at 33 hour intervals	Accelerated weathering	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles; 264 hr. = 1 equiv. yr.	After 3 equiv. yrs. of exposure/test, no visible damage and haze < 4%.
Edge Attachment	Flex. beams, approx. 3"x15", simulating design cross-section and edge fixity, per Sect. 4.4; 3- or 4-point loaded at high rate (2000 in/min)	Unexposed	Critical combined load condition during bird impact and/or in-flight	Successful edge designs will exceed design ultimate load without failure.
Impact (Subscale)	12" sq. plates, free edge, air cannon tested using 1" dia. steel sphere	Baseline (unexposed) and accelerated weathering	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles; 264 hr. = 1 equiv. yr.	After 3 equiv. yrs. of exposure/test, thresold-of-failure energy to be within 15% of unexposed value.
Pressure/Temperature/Durability	Full-scale transparency installed in airframe support structure, Bldg. 65 Test Facility at WPAFB	Simulated temp. and press. mission profiles combined with critical ground environment incorporating realistic rates to evaluate thermal shock		Successfully withstand 2000 simulated flight hours and 3 equiv. yrs. of flightline exposure/test.
Birdstrike	Full-scale transparency installed in airframe support structure; AEDC test per ASTM F330-79.	Unexposed; following flight/flightline testing in Bldg. 65 Facility; and from in-service at yearly intervals.	In-flight birdstrike	Pass impact of 4 lb. bird at specified velocity.

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TABLE [illegible]

DURABILITY EVALUATION OF HIGH PERFORMANCE USAF TRANSPARENCY SYSTEMS
ACRYLIC FACED/POLYCARBONATE LAMINATE* SUMMARY

TEST PARAMETER	TEST METHOD	ENVIRONMENTAL CONDITION	SIMULATION	ACCEPTANCE CRITERIA
Surface/Chemical Craze	1"x7" beam per MIL-P-8184E, Para. 4.5.5, ASTM F484-77 or equiv.; or 1"x15" incremental stress beam per Sect. 4.1; isopropyl alcohol; f=2000 psi	Accelerated weathering	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles; 264 hrs. = 1 equiv. yr.	No crazing after 3 equiv. yrs. of exposure/test
Haze/Transmittance	FTM 406, Method 3022, or equivalent			After 3 equiv. yrs. of exposure/test, haze < 4% and luminous transmittance to be within 2% of unexposed value.
Interlaminar Bond Integrity (Delamination)				
(a) Flatwise Tension	Use ASTM D952 or F521-77 as guideline; urethane interlayer may be undercut to 1 sq. in. in test area per Sect. 4.7			After 3 equiv. yrs. of exposure/test, interlayer flatwise tensile stress shall exceed design ultimate without failure.
(b) Torsional Shear	Use ASTM D229 as guideline; lock inner portion to load cell, applying torque to outside of specimen as per Sect. 4.8			After 3 equiv. yrs. of exposure/test, interlayer shear stress shall exceed design ultimate without failure.
(c) Wedge Peel	Use ASTM D3762-79 as guideline; insert and hold wedge into machined slot in interlayer of 1"x10" specimen per Sect. 4.9			After 3 equiv. yrs. of exposure/tests, no measurable delamination length for [illegible] hrs after insertion of wedge.
Impact (a) Coupon	Falling weight beams per ASTM [illegible] or Sect. 4.2 (high rate MTS beam test)	Baseline (unexposed) and accelerated weathering plus stress	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles, 264 hrs. = 1 equiv. yr. in combination with an outer fiber stress of 1000 psi.	After 3 equiv. yrs. of exposure/test, structural ply threshold of failure to be within 15% of unexposed value.
(b) Subscale	12" sq. plates, free edge, air cannon tested using 1" dia. steel sphere	Baseline (unexposed) and accelerated weathering	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles; 264 hr. = 1 equiv. yr.	After 3 equiv. yr. of exposure/test, structural ply threshold of failure to be within 15% of unexposed value.
Thermal Shock	In accordance with ASTM F520-77, plus rapid drying in partial vacuum	Accelerated weathering	Refer to ASTM F520-77	After 3 equiv. yrs. of exposure/test, [illegible] loss of coating, cracking, spalling, [illegible] or other [illegible]
Abrasion Resistance (a) In-flight	3" sq. samples per Sect. 4.3; following QUV and abrasion, measure haze with a std. hazemeter	Accelerated weathering plus salt blast abrasion	(264 hrs. acc. weathering followed by 8 cycles of salt blast) x 1 = 1 equiv. yr, x 2 = 2 equiv. yr, x 3 = 3 equiv. yr.	After exposure/test, haze [illegible] 4% after 1 equiv. yr, haze [illegible] 5% after [illegible] equiv. yr., haze [illegible] after 3 equiv. yr.
(b) Flightline	4"x4" test samples subjected to 50 normal cleanings at 33 hr. intervals	Accelerated weathering	QUV, 120°F, 7 hr. UV/5 hr. condensation cycles; 264 hr. = 1 equiv. yr.	After 3 equiv. yrs. of exposure/test, no visible damage and haze < 4%.
Edge Attachment	Flex. beams, approx. 3"x15", simulating design cross-section and edge fixity, per Sect. 4.4; 3- or 4-point loaded at high rate (2000 in/min)	Unexposed	Critical combined load condition during bird impact and/or in-flight	Successful edge designs will exceed design ultimate load without failure.
Pressure/Temperature/Durability	Full-scale transparency installed in airframe support structure; Bldg. 65 Test Facility at WPAFB	Simulated temp. and press. mission profiles combined with critical ground environment, incorporating realistic rates to evaluate thermal shock		Successfully withstand 2000 simulated flight hours and 3 equiv. yrs. of flightline exposure/test.
Birdstrike	Full-scale transparency installed in airframe support structure; AEDC test per ASTM F330-79	Unexposed; following flight/flightline testing in Bldg. 65 facility and from in-service at yearly intervals	In-flight birdstrike	Pass impact of 4 lb. bird at specified velocity.

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SECTION 2

TEST REQUIREMENTS

2.1 MONOLITHIC STRETCHED ACRYLIC

2.1.1 Surface/Chemical Craze

Conduct craze resistance tests in accordance with MIL-P-25690A, paragraph 4.6.7 or ANSI/ASTM F484-77 or equivalent, using isopropyl alcohol and ethylene glycol with an outer fiber stress of 2,000 psi. The test specimens shall be conditioned per paragraph 3.1 of this document prior to test and shall exhibit no evidence of crazing after test.

Paragraph 4.1 describes an optional test method for conducting craze resistance tests that concurrently measures the time-to-craze corresponding to different stress levels. A load that will result in a maximum outer fiber stress of approximately 2500 psi is recommended.

2.1.2 Haze/Transmittance

Conduct haze and luminous transmittance tests in accordance with FTM 406, Method 3022, or equivalent. The test specimens shall be conditioned per paragraph 3.1 of this document prior to test. After exposure/test, the percent of haze shall not exceed 4% and the luminous transmittance shall be within 2% of the original unexposed value.

2.1.3 Impact

Determine the energy required to initiate failure in monolithic stretched acrylic beams subjected to impact loading

in accordance with ASTM Test Method F736-81. Unexposed specimens shall be tested in addition to specimens conditioned per paragraph 3.1 of this document. After exposure/test, the change in impact resistance shall not exceed ±15% of the unexposed value.

Paragraph 4.2 describes an optional test method for measuring impact resistance.

2.1.4 Thermal Shock

To verify that monolithic or laminated transparency materials are capable of withstanding the temperature extremes anticipated for high performance flight regimes, conduct thermal shock tests in accordance with ASTM Test Method F520-77, modified to include rapid drying in a partial vacuum. Precondition test samples per Paragraph 3.1. After exposure/test, there shall be no cracking, spalling, loss of transparency, or other visible deterioration.

2.1.5 In-Flight Abrasion Resistance

Conduct simulated in-flight abrasion resistance tests in accordance with paragraph 4.3 of this document. Three sets of specimens shall be conditioned per paragraph 3.2 of this document prior to test. After exposure/test, the percent of haze shall not exceed 4% after one equivalent year; 5% after two equivalent years; or 6% after three equivalent years.

2.1.6 Flightline Abrasion Resistance

Using the accelerated weathering exposure of Paragraph 3.1, and based on 792 hours run time, condition a set of 4x4-inch test samples for three equivalent years. At 33 hour intervals, subject the test samples to 50 normal cleaning

operations using a solution of 1 part water to 1 part isopropyl alcohol with Kaydry disposable towels. There shall be no visible damage to the specimens; the resultant haze shall not exceed 4%.

2.1.7 Edge Attachment

Structurally, edge attachments are a primary design consideration, especially when impacts are near the edges. The generation of design tradeoff data required to finalize a transparency cross-section and associated edge design would be prohibitive in terms of dollars, manpower, availability of parts, and calendar time if fully obtained from the testing of full-scale flight hardware. Therefore, unexposed flexure beam specimens, simulating the candidate production transparency cross-sections, shall be tested in accordance with paragraph 4.4 to screen the candidate configurations in the laboratory. Successful edge designs will exceed the design ultimate load without failure.

2.1.8 Subscale Impact

Determine the velocity required to initiate failure in monolithic stretched acrylic plates subjected to ballistic impact in accordance with paragraph 4.5. Unexposed specimens shall be tested in addition to specimens conditioned per paragraph 3.1. After exposure/test, the change in threshold-of-failure velocity shall not exceed ±15% of the unexposed value.

2.1.9 Full Scale Pressure/Temperature/Durability Test

The full scale test article, consisting of the test transparency installed in a representative airframe support structure, being typical of production units, shall be capable of successfully withstanding the simulated temperature and pressure mission profiles, incorporating realistic rates to evaluate

thermal shock, and combined with critical ground environment conditions. These tests will be conducted at a suitable facility such as the one in Building 65 at Wright-Patterson Air Force Base (reference Section 3.4).

2.1.10 Full Scale Birdstrike

The full scale test article, consisting of the test transparency installed in a representative airframe support structure, being typical of production units, shall be capable of successfully withstanding the impact of a four-pound bird at specified impact locations and velocities. There shall be no penetration of bird debris into the cockpit enclosure, spalling, or deflection of the transparency or support structure that could result in serious pilot injury or inability to negotiate a safe landing. These tests will be conducted at a suitable facility such as the one at the Arnold Engineering Development Center in accordance with ANSI-ASTM F330-79. Full-scale transparencies to be tested will include (a) unexposed baseline transparencies, and (b) the flight/flightline test article from the Building 65 facility or similar facility. In addition, transparencies will be taken from in-service and tested at yearly intervals, the oldest transparencies being selected for such tests.

2.2 COATED MONOLITHIC POLYCARBONATE

2.2.1 Surface/Chemical Craze

Conduct craze resistance tests in accordance with MIL-P-83310, paragraph 4.5.5.2, or ANSI/ASTM F484-77 or equivalent using isopropyl alcohol and ethylene glycol with an outer fiber stress of 2,000 psi. The test specimens shall be conditioned per paragraph 3.1 prior to test and shall exhibit no evidence of crazing after test.

Paragraph 4.1 describes an optional test method for conducting craze resistance tests that concurrently measures the

time-to-craze corresponding to different stress levels. A load that will result in a maximum outer fiber stress of approximately 2500 psi is recommended.

2.2.2 Haze-Transmittance

Conduct haze and luminous transmittance tests in accordance with FTM 406, Method 3022, or equivalent. The test specimens shall be conditioned per paragraph 3.1 of this document prior to test. After exposure/test, the percent of haze shall not exceed 4% and the luminous transmittance shall be within 2% of the original unexposed value.

2.2.3 Coating Adhesion

Rain erosion specimens shall be conditioned in accordance with paragraph 3.3 and subjected to rain impingement test conditions per paragraph 4.6. After exposure/test, the percent of coating removal shall be determined by scanning electron microscopic examination. Success shall be determined by no substantial amount of coating removal or significant optical clarity degradation after 5 minutes of exposure at 500 mph in a 1-inch/hour rainfall.

2.2.4 Coating Embrittlement

Unexposed beam specimens, in addition to beam specimens conditioned per paragraph 3.3, shall be subjected to impact tests in accordance with ASTM Test Method F736-81 or paragraph 4.2. After exposure/test, the change in impact resistance shall not exceed ±15% of the unexposed value.

2.2.5 Thermal Shock

To verify that monolithic or laminated transparency materials are capable of withstanding the temperature extremes anticipated for high performance flight regimes, conduct thermal shock tests in accordance with ASTM Test Method F520-77, modified to include rapid drying in a partial vacuum. Precondition test samples per Paragraph 3.1. After exposure/test, there shall be no loss of coating, cracking, spalling, loss of transparency, or other visible deterioration.

2.2.6 In-Flight Abrasion Resistance

Conduct simulated in-flight abrasion resistance tests in accordance with Paragraph 4.3. Three sets of specimens shall be conditioned per Paragraph 3.2 prior to test. After exposure/test, the percentage of haze shall not exceed 4% after one equivalent year, 5% after two equivalent years; or 6% after three equivalent years.

2.2.7 Flightline Abrasion Resistance

Using the accelerated weathering exposure of Paragraph 3.1, and based on 792 hours run time, condition a set of 4x4-inch test samples for three equivalent years. At 33 hour intervals, subject the test samples to 50 normal cleaning operations using a solution of 1 part water to 1 part isopropyl alcohol with Kaydry disposable towels. There shall be no visible damage to the specimens; the resultant haze shall not exceed 4%.

2.2.8 Edge Attachment

Structurally, edge attachments are a primary design consideration, especially when impacts are near the edges. The generation of design tradeoff data required to finalize a transparency cross-section and associated edge design would be prohibitive in terms of dollars, manpower, availability of parts, and calendar time if fully obtained from the testing of full-scale flight hardware. Therefore, unexposed flexure beam specimens,

simulating the candidate production transparency cross-sections, shall be tested in accordance with paragraph 4.4 to screen the candidate configurations in the laboratory. Successful edge designs will exceed the design ultimate load without failure.

2.2.9 Subscale Impact

Determine the velocity required to initiate failure in coated monolithic polycarbonate plates subjected to ballistic impact in accordance with paragraph 4.5. Unexposed specimens shall be tested in addition to specimens conditioned per paragraph 3.1. After exposure/test, the change in threshold-of-failure velocity shall not exceed ±15% of the unexposed value.

2.2.10 Full Scale Pressure/Temperature/Durability Test

The full scale test article, consisting of the test transparency installed in a representative airframe support structure, being typical of production units, shall be capable of successfully withstanding the simulated temperature and pressure mission profiles, incorporating realistic rates to evaluate thermal shock, and combined with critical ground environment conditions. These tests will be conducted at a suitable facility such as the one in Building 65 at Wright-Patterson Air Force Base (reference Section 3.4).

2.2.11 Full Scale Birdstrike

The full scale test article, consisting of test transparency installed in a representative airframe support structure, being typical of production units, shall be capable of successfully withstanding the impact of a four-pound bird at specified impact locations and velocities. There shall be no penetration of bird debris into the cockpit enclosure, spalling, nor deflection of the transparency or support structure that could result in serious pilot injury or inability to negotiate a safe landing. These tests will be conducted at a suitable facility such as the one at Arnold Engineering Development Center in accordance with ANSI-ASTM F330-79. Full-scale transparencies to be tested

will include (a) unexposed baseline transparencies, and (b) the flight/flightline test article from the Building 65 facility or similar facility. In addition, transparencies will be taken from in-service and tested at yearly intervals, the oldest transparencies being selected for such tests.

2.3 ACRYLIC FACED/POLYCARBONATE LAMINATE

2.3.1 Surface/Chemical Craze

Conduct craze resistance tests in accordance with MIL-P-8184B, Paragraph 4.5.5, or ANSI/ASTM F484-77 or equivalent using isopropyl alcohol with an outer fiber stress of 2,000 psi. The test specimens shall be conditioned per Paragraph 3.1 prior to test and shall exhibit no evidence of crazing after test.

Paragraph 4.1 describes an optional test method for conducting craze resistance tests that concurrently measures the time-to-craze corresponding to different stress levels. A load that will result in a maximum outer fiber stress of approximately 2,500 psi is recommended.

The stress at the acrylic outer surface of a laminate would be influenced by the characteristics of the other plies in the laminate and cannot be calculated the same way as for a monolithic test coupon. Strain gages could be used to obtain values which could be converted to stresses (see discussion in Section 4.1). Another approach would involve removing the outer acrylic ply from the laminate (by cutting through the interlayer), then testing the acrylic as a monolithic beam.

2.3.2 Haze-Transmittance

Conduct haze and luminous transmittance tests in accordance with FTM 406, Method 3022, or equivalent. The test specimens shall be conditioned per Paragraph 3.1 of this document prior to test. After exposure/test, the percent of haze shall not exceed 4% and the luminous transmittance shall be within 2% of the original unexposed value.

2.3.3 Interlaminar Bond Integrity (Delamination)

2.3.3.1 Flatwise Tension

Conduct flatwise tension tests using ASTM D 952 or ASTM F521-77 as a guideline and modified per Section 4.7 to determine the flatwise tensile stress (normal to the surface) required to delaminate the transparency material. The test specimens shall be conditioned per paragraph 3.1 prior to test. After exposure/test, flatwise tensile stress of the interlayers shall exceed the design ultimate value without failure.

2.3.3.2 Torsional Shear

Conduct torsional shear tests using ASTM D229 as a guideline and modified per Section 4.8 to determine the shear stress (parallel to the surface) required to delaminate the transparency material. The test specimens shall be conditioned per paragraph 3.1 prior to test. After exposure/test, the interlayer shear stress shall exceed the design ultimate value without failure.

2.3.3.3 Wedge Peel

Conduct wedge peel tests using ASTM D3762-79 as a guideline and modified per Section 4.9 to qualitatively evaluate the interlaminar peel-creep strength of the transparency interlayer. The test specimens shall be conditioned per paragraph 3.1 prior to test. Insert the aluminum or stainless steel wedge into the specimen slot, using a fixture to hold the wedge in position for the duration of the test. There shall be no measurable delamination length for 100 hours after insertion of the wedge.

2.3.4 Impact

Determine the energy required to initiate failure in the structural ply of laminated beams subjected to impact loading in accordance with ASTM Test Method F736-81 or paragraph 4.2 of this document. Unexposed specimens shall be tested in

addition to specimens conditioned per paragraph 3.3. After exposure/test, the change in impact resistance shall not exceed ±15% of the unexposed value.

2.3.5 Thermal Shock

To verify that monolithic or laminated transparency material are capable of withstanding the temperature extremes anticipated for high performance flight regimes, conduct thermal shock tests in accordance with ASTM Test Method F520-77, modified to include rapid drying in a partial vacuum. Precondition test samples per paragraph 3.1. After exposure/test, there shall be no delamination, cracking, spalling, loss of transparency, or other visible deterioration.

2.3.6 In-Flight Abrasion Resistance

Conduct simulated in-flight abrasion resistance tests in accordance with paragraph 4.3. Three sets of specimens shall be conditioned per paragraph 3.2 prior to test. After exposure/test, the percentage of haze shall not exceed 4% after one equivalent year; 5% after two equivalent years; or 6% after three equivalent years.

2.3.7 Flightline Abrasion Resistance

Using the accelerated weathering exposure of paragraph 3.1, and based on 792 hours run time, condition a set of 4x4-inch test samples for three equivalent years. At 33 hour intervals, subject the test samples to 50 normal cleaning operations using a solution of 1 part water to 1 part isopropyl alcohol with Kaydry disposable towels. There shall be no visible damage to the specimens; the resultant haze shall not exceed 4%.

2.3.8 Edge Attachment

Structurally, edge attachments are a primary design consideration, especially when impacts are near the edges. The generation of design tradeoff data required to finalize a transparency cross-section and associated edge design would be prohibitive in terms of dollars, manpower, availability of parts, and calendar time if fully obtained from the testing of full-scale flight hardware. Therefore, unexposed flexure beam specimens, simulating the candidate production transparency cross-sections, shall be tested in accordance with paragraph 4.4 to screen the candidate configurations in the laboratory. Successful edge designs will exceed the design ultimate load without failure.

2.3.9 Subscale Impact

Determine the velocity required to initiate failure of the structural ply of acrylic faced/polycarbonate laminated plates subjected to ballistic impact in accordance with paragraph 4.5. Unexposed specimens shall be tested in addition to specinens conditioned per paragraph 3.1. After exposure/test, the change in threshold-of-failure velocity shall not exceed ±15% of the unexposed value.

2.3.10 Full Scale Pressure/Temperature/Durability Test

The full scale test article, consisting of the test transparency installed in a representative airframe support structure, being typical of production units, shall be capable of successfully withstanding the simulated temperature and pressure mission profiles, incorporating realistic rates to evaluate thermal shock, and combined with critical ground environmental conditions. These tests will be conducted at a suitable facility such as the one in Building 65 at Wright-Patterson Air Force Base (reference Section 3.4).

2.3.11 Full Scale Birdstrike

The full scale test article, consisting of the test transparency installed in a representative airframe support structure, being typical of production units, shall be capable of successfully withstanding the impact of a four-pound bird at specified impact locations and velocities. There shall be no penetration of bird debris into the cockpit enclosure, spalling, nor deflection of the transparency or support structure that could result in serious pilot injury or inability to negotiate a safe landing. These tests will be conducted at a suitable facility such as the one at the Arnold Engineering Development Center in accordance with ANSI/ASTM F330-79. Full-scale transparencies to be tested will include (a) unexposed baseline transparencies, and (b) the flight/flightline test article from the Building 65 facility or similar facility. In addition, transparencies will be taken from in-service and tested at yearly intervals, the oldest transparencies being selected for such tests.

SECTION 3

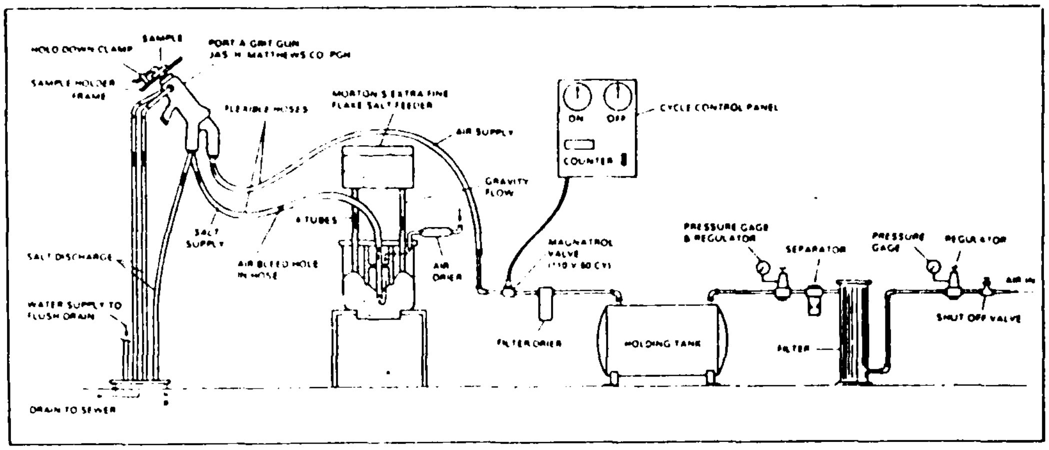
EXPOSURE SIMULATION

3.1 ACCELERATED WEATHERING

The Q.U.V. Accelerated Weathering Tester, manufactured by the Q-Panel Company, Cleveland, Ohio, combines the effects of the UV wavelengths of sunlight with heat and condensation to simulate accelerated weathering. Using the Q.U.V. tester, an operating temperature of 120°F, alternating cycles of 7 hours UV followed by 5 hours condensation, and based on a year of natural weathering being simulated by 264 hours run time; condition the test samples for 792 hours or three equivalent years.

3.2 ACCELERATED WEATHERING PLUS SALT BLAST ABRASION

The major source of abrasion encountered when a plane flies through a cloud containing ice crystals is impact abrasion. In an attempt to simulate this service condition, PPG Industries of Pittsburgh, Pennsylvania has developed the salt blast abrasion tester shown in Figure 3.2.1. The salt abrader, although complicated in appearance, is a simple machine in principle. As the shut-off valve is turned on, the holding tank fills to the pressure selected by the pressure regulator. As blasting is initiated, moving air travels to the exit port in the specimen mount, passing an opening leading to the salt supply. A vacuum is created at this opening, thereby forcing salt into the airstream. The salt then moves on to impact the specimen surface. Salt was chosen as the abrasive for the following reasons:



The PPG Salt Blast Abrader attempts to simulate flight conditions by impacting the plastic test sample with successive 1/2 second blasts of minute salt particles. The abraded area is a circle one-inch in diameter, and four test areas are produced on a three-inch square sample. The increase in haze is used as a measure of the abrasion resistance. A major advantage of this abrader is that the test piece need not be flat. Actual curved sections from windshields have been tested.

The salt blast abrader is based on a device used to sand blast trademarks, etc. on glass. After considerable trial and many errors, modifications were made which enabled PPG to produce a uniformly abraded area by controlling the following variables:

1. Air pressure--15 psi--70 mph as sample
2. Salt delivery per 1/2 second blast --(1.9 grams/cycle)
3. No recycling of the salt
4. Accurate timing control of the 1/2 second on and 1 1/2 second off cycle
5. Automatic control of the number of cycles
6. Accurately sized free-flowing salt

Figure 3.2.1. PPG Salt Blast Abrasion Tester.

1. Moh's hardness of 2.5 as compared with 1.5 for ice, where Moh's scale of relative hardness of a mineral ranges from 1 for talc to 10 for diamond, or as determined by which mineral can scratch the one preceding it.
2. Non-toxic and water soluble.
3. Readily available in controlled particle size at a few cents per pound.

The particular grade of salt chosen after some experimentation is Morton's Extra Fine Flake. This is commercially available pan crystallized, non-pulverized salt containing about 1/2% of tricalcium phosphate which prevents caking.

Using the Q.U.V. Accelerated Weathering Tester in conjunction with the PPG Salt Blast Abrasion Tester, condition three sets of test samples as follows:

(264 hours accelerated weathering followed by 8 cycles of salt abrasion) x 1 = 1 equivalent year set;
x 2 = 2 equivalent year set; and
x 3 = 3 equivalent year set.

3.3 ACCELERATED WEATHERING PLUS STRESS

To fully realize the contributing effects of stress, UV, moisture, and temperature, it is recommended that test samples be restrained to induce stress prior to being exposed to the accelerated weathering condition of Paragraph 3.1. Figure 3.3.1 presents a fixture for inducing an outer fiber stress of 1,000 psi into an impact beam specimen; a scaled-down version to be used for rain erosion specimens.

3.4 BUILDING 65 (WPAFB) ENVIRONMENTAL TEST FACILITY

The recently completed Building 65 Environmental Test Facility at WPAFB enables the Air Force to superimpose simulated

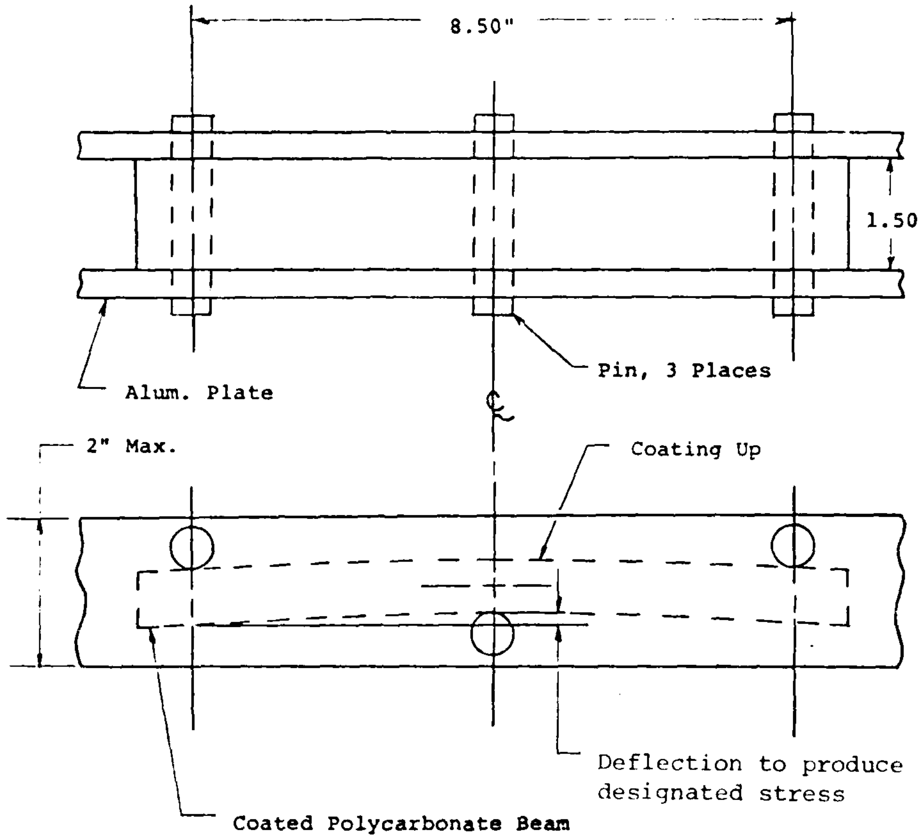


Figure 3.3.1. Beam Loading Fixture.

flightline exposure consisting of ultraviolet radiation/thermal/moisture cycles into the critical in-flight pressure/temperature test spectrum. In addition, cleaning and polishing cycles with approved chemicals and clean cloth are represented. Temperature rate changes of 100°F per minute rise rate and 33°F per minute cooling rate are typical.

The approach used to subject the test articles to various flight and ground environmental exposures is to alternate between the ground and flight environments, simulating what occurs in the real world.

The basic F-16 laminated canopy test program is a 2000 flight hour simulation of the flight environment. In addition, 104 cycles of the flightline environment are performed to simulate 3 years of UV radiation in a hot and humid environment, plus cleaning. The 2000 flight hour simulation is a composite of thirteen different missions. The duration of each mission profile and the number of cycles run is given below.

Mission No.	Duration Each Cycle (minutes)	Total No. of Cycles
1	90.0	67
2	120.0	100
3	57.0	421
4	65.0	185
5	65.0	185
6	173.0	69
7	138.0	87
8	41.5	145
9	120.0	50
10	140.0	43
11	330.0	18
12	39.5	153
13	23.0	5

The temperature and pressure profiles for these thirteen missions are run for standard atmosphere (80% of missions), hot atmosphere (10% of missions), and cold atmosphere (10%) conditions; mission #13 being an exception as it will be run 4 times for standard atmosphere and 1 time for cold atmosphere conditions.

The test canopy shall be cleaned using the cleaning solutions and materials authorized for use on installed canopies. The canopy shall be subdivided into sections, each section being cleaned with different cleaning solutions. The cleaning shall be performed during each changeover from the flightline environment to the flight environment testing.

SECTION 4

NON-STANDARD TEST METHODS

4.1 INCREMENTAL STRESS CRAZE TEST METHOD

Bending stress decreases monotonically along the length of a cantilever beam specimen from a maximum value at the fulcrum to a minimum of zero at the point of load application (neglecting locally induced stresses at the point of load application). Thus, discrete points along the beam's length have unique values of bending stress associated with them.

A chemical applied along the length of the beam would cause crazing first at higher stressed points and then progressively at lower stressed points. By recording time for crazing to occur at each point, and correlating these times with the bending stress values at each point, many stress versus time-to-craze points (in fact, an entire curve) can be obtained from a single specimen and test.

The hardware for the modified test method (Figure 4.1.1) is very similar to that of the standard test method. The fixturing, including cantilever supports and load application gear, are identical. The specimen dimensions have been revised, with the width being 1±0.03 in. (25.4±0.8 mm) and the length being 15±0.05 in. (381±1.27 mm). The thickness is that of the as-received sheet of material. The extended specimen length facilitates correlation of craze location with discrete points (and thus values of bending stress) along the beam. These points are marked at one-quarter and one-half inch intervals as shown in Figure 4.1.1. Either laminated or monolithic specimens can be tested.

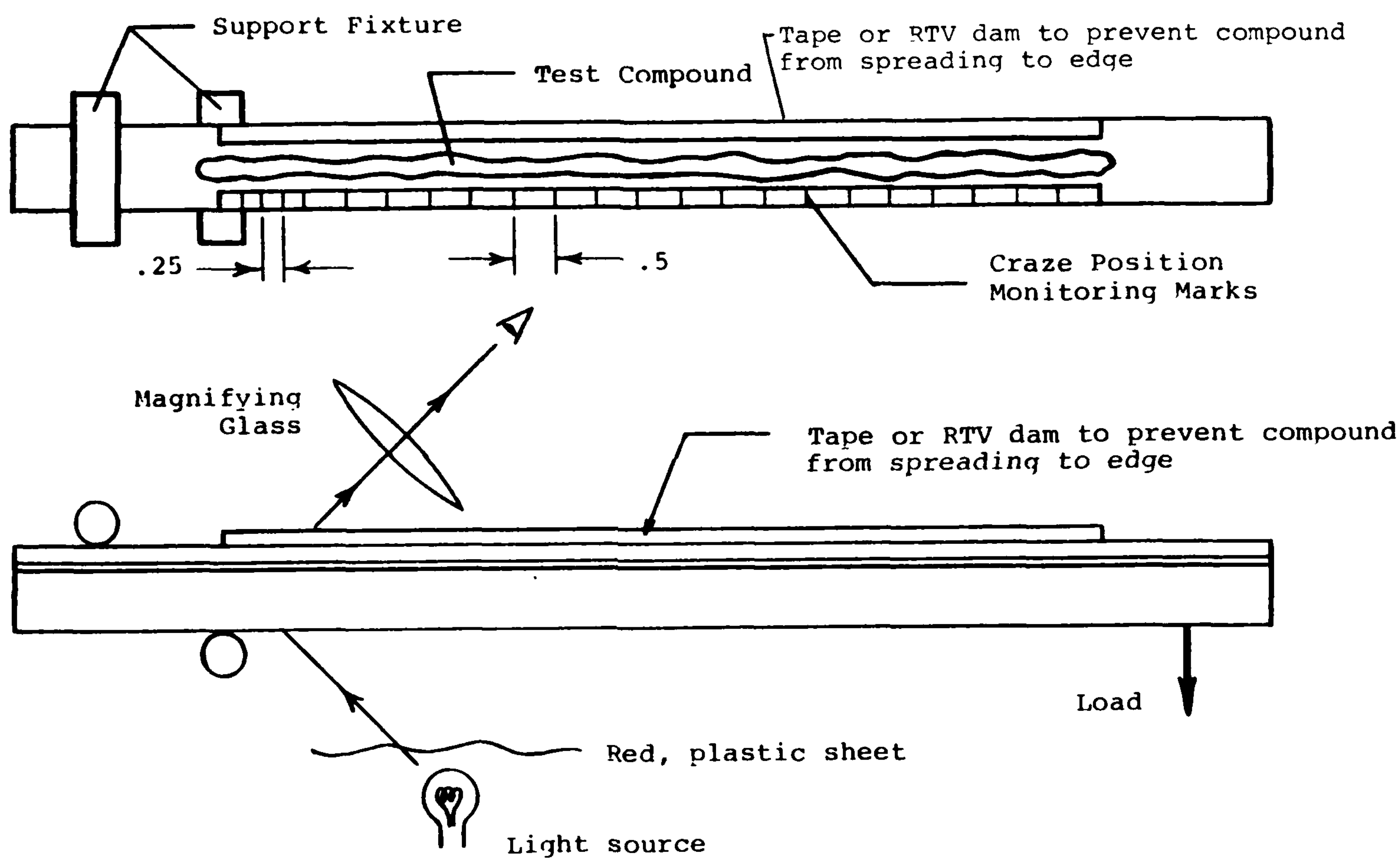


Figure 4.1.1. Setup for Modified Crazing Tests.

It is necessary to determine the bending stress distribution over the beam length so that crazing locations can be matched with stress values. This distribution can not be computed using elementary beam theory for laminated material since the low-modulus interlayers cause plane sections normal to the specimen axis to warp severely under test load.

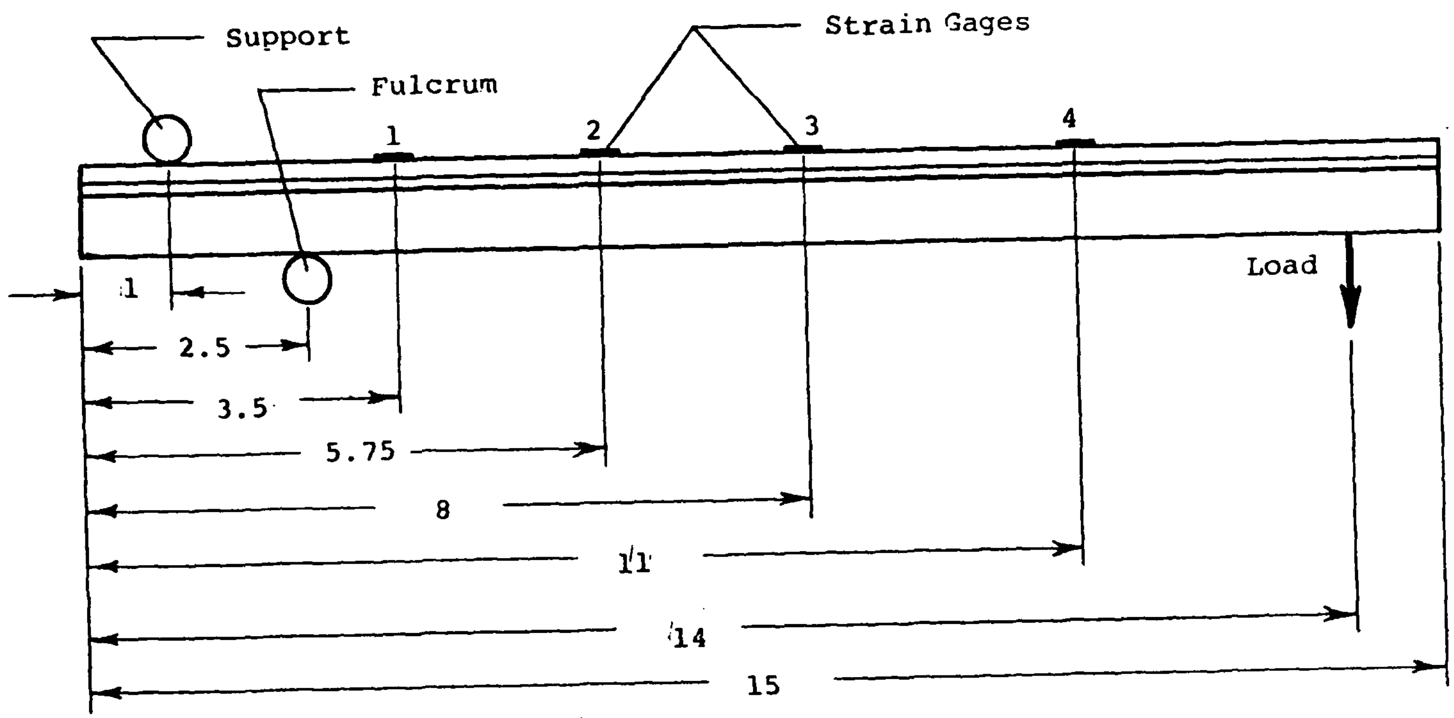
Four strain gages are, therefore, employed to determine the bending stress distribution (see Figure 4.1.2). Another approach would involve removing the outer acrylic ply from the laminate (by cutting through the interlayer), then testing the acrylic as a monolithic beam. For the strain-gaged beam, a load that will result in a maximum fiber stress of approximately 2500 psi at gage 1 is recommended. The strain readings do not stabilize, but increase continuously under constant load. Since the duration of actual tests is 40 minutes, it is necessary to account for this viscoelastic behavior ("creep").

The increase in strain is monitored and percent "creep" curves computed for the gages; the percent "creep" being defined as

$$\frac{\epsilon_t - \epsilon_o}{\epsilon_o} \times 100\%$$

where ϵ_o is the strain at the instant of load application and ϵ_t is the strain at some later time. An average of "creep" is determined from the computed curves, and used to correct the strain reading recorded for each gage at the instant of load application. Limited test data indicates that the percent error between the corrected and actual values of strain at any time during a test will be within ±3%. The corrected strains are converted to stresses using Hooke's law.

The specimens are loaded and allowed to stabilize for 10 minutes. The chemical being evaluated is then applied along



NOTE: All dimensions in inches.

Figure 4.1.2. Setup for Stress Calibration of Beam.

the length of the beams. The time for crazing to initiate at each craze-propagation mark is recorded. The test is completed when crazing reaches the point of load application or when the time elapsed from the beginning of chemical application is 30 minutes. The chemical should be renewed as needed during the testing. Plot the time-to-craze versus upper-ply surface stress along the length of the beam specimen. A typical plot is shown as Figure 4.1.3.

4.2 HIGH RATE MTS BEAM TEST

Three-point beam specimens shall be 1.500±.010 inches wide, nominal 10.50 inches long, and as-received thickness. Beam edges shall be milled and inspected using polarized light to ensure that the level of residual machining stress is low; beam ends may remain as band-sawed. Additionally, the corners of the specimen edges must be deburred using #400 emery paper in the region of critical loading; the goal being to initiate failure from the central surface and not the edges.

The high-rate MTS beam test is an instrumented flexure test utilizing three-point simply-supported loading. Figure 4.2.1 shows the equipment used to conduct these tests; the MTS test machine being a high performance general purpose mechanical loading apparatus with high level control and data gathering capabilities. It consists of the following major components: a servohydraulic power pump, a specimen holding fixture, a reaction load frame, appropriate transducers, an electronic feedback controller operating the actuator through an electrically controlled hydraulic servovalve, and suitable data gathering, storage, and recording instrumentation. It is a system of matched components manufactured by MTS Systems Corporation, Minneapolis, Minnesota. A mounting fixture is used to provide three-point simply-supported loading to the center of each specimen as shown in Figure 4.2.2; the contact radius of each loading support being 3/8 inch. The span between supports provides an 8:1 span-to-depth

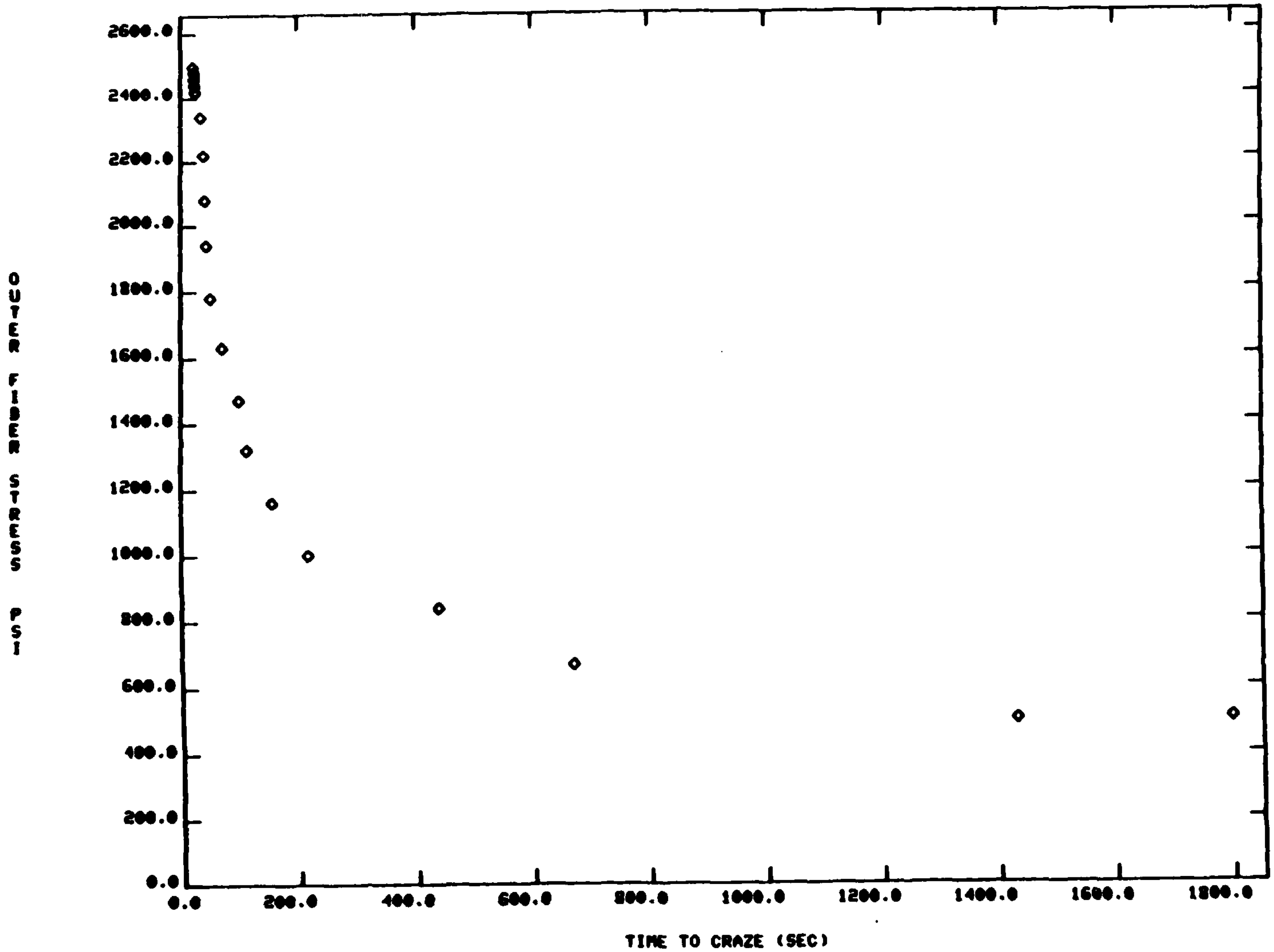
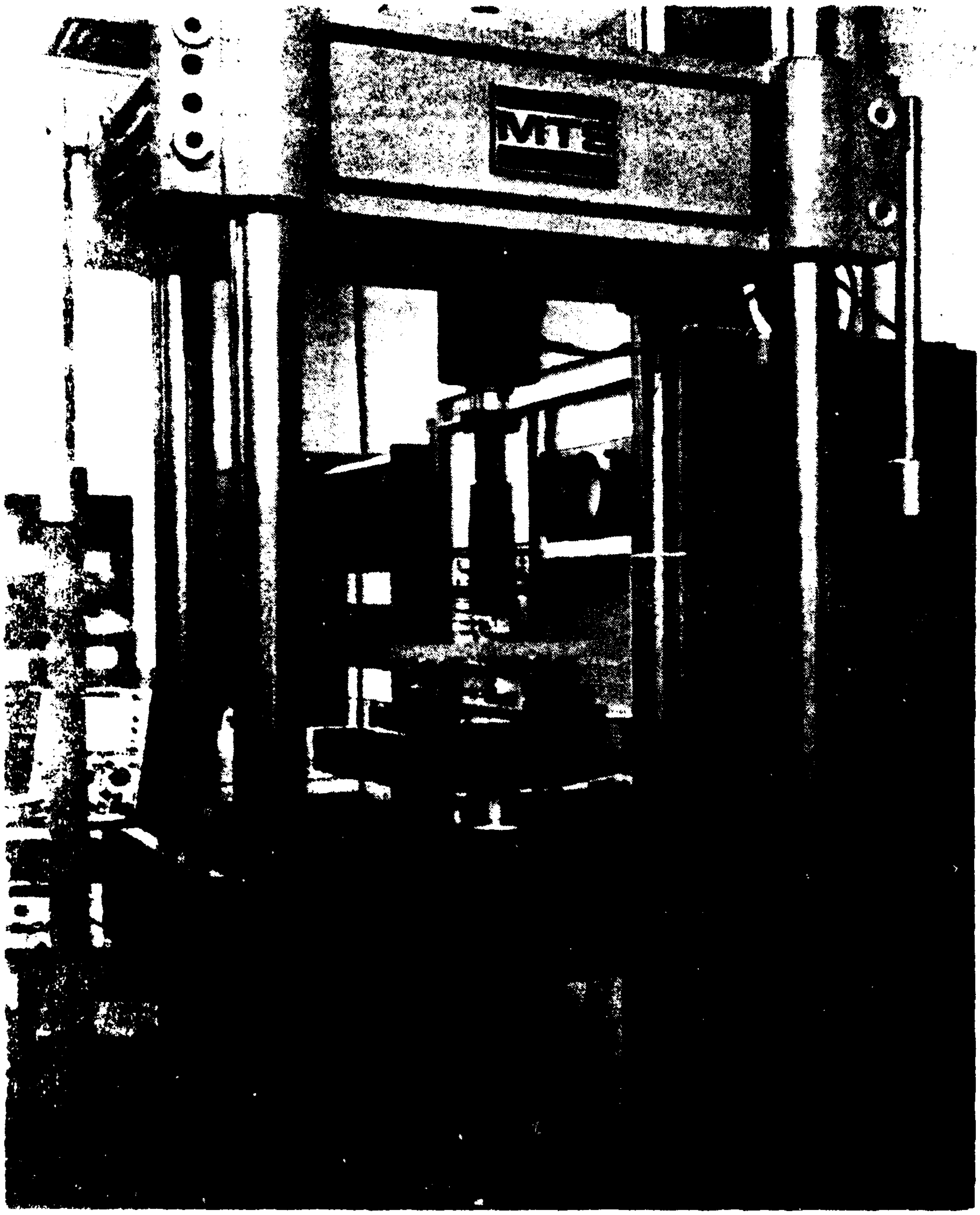
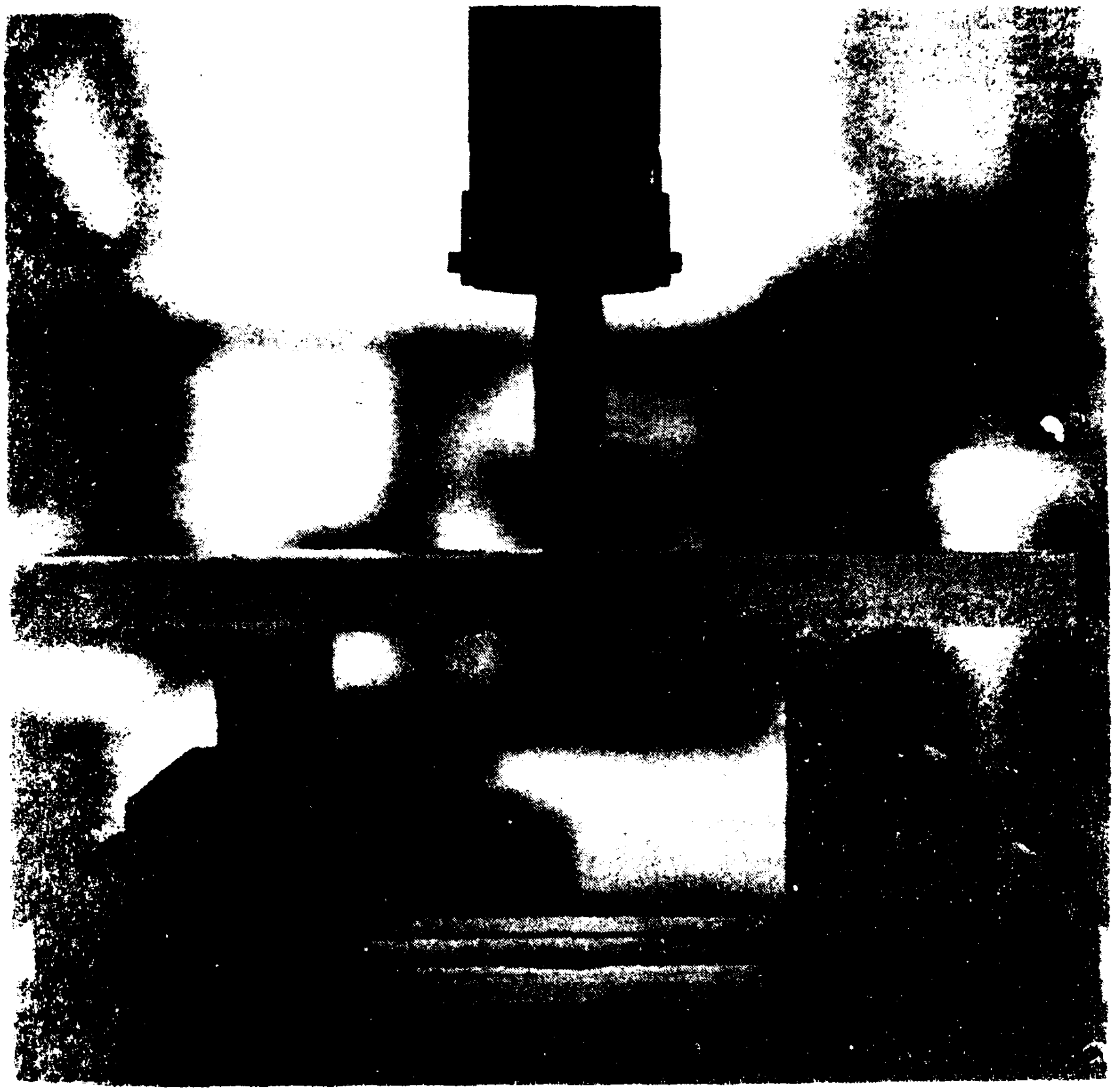


Figure 4.1.3. Craze Data for Single Specimen.





ratio. The specimen is centered in the fixture with the test surface down, producing tension in the test surface under investigation. The two outer supports are part of the loading yoke below the specimen. This yoke is positioned above the vertically mounted actuator, and is attached to the top of the ram; the yoke moving upward to load the specimen. Ram position is measured by an LVDT (Linear Variable Differential Transformer), with this signal being sent as the feedback signal to the analog electronic feedback controller for the actuator; the command signal for the controller being generated by a selectable function generator. Displacement rate is controlled to be 2,000 inches/minute or more. Peak displacement is set at a selected value (nominally 2.50 inches). The center loading support remains stationary during testing. The upper part of the center support is attached to the stationary load frame. Both load and displacement are set at zero when the specimen just touches the loading fixture. The calibrated output signals of both the LVDT and load cell are captured in a dual channel digital transient waveform recorder and then played back on an X-Y recorder to document load versus displacement for each high-rate MTS beam test specimen.

4.3 SALT BLAST ABRASION

All test samples are cut to 3-inch square, code marked, and the original (unexposed) haze read on a Gardner Hazemeter. After the specified Q.U.V. exposure, check out and operate the salt blast abrader to accomplish the specified abrasion.

Use intermittent blasts since a single, continuous blast reduces the system pressure to nearly zero. A one-half second blast followed by a two second pressure recovery at an operating pressure of 20 psig is recommended. These settings give relatively fast surface wear (compared to lower pressures) and reduced salt leakage from the specimen mount area (compared to

higher pressures). An overall drop in pressure of about 5 psig occurs between the initial blast and succeeding blasts, so it is necessary to set the initial pressure to 25 psig with the pressure regulator.

Following abrasion, measure the haze of the abraded specimen with a Gardner Hazemeter after the following specimen clean-up steps are accomplished.

1. Rinse (do not rub, wipe, or brush) off loose salt with distilled water.
2. Rinse the specimen with a 50-50 mixture of isopropyl alcohol and distilled water (similar to the cleaning fluid used on actual transparencies).
3. Rerinse with distilled water.
4. Spray off excess liquid from the abrasion with clean compressed air.
5. Wipe the rest of the beam dry with a clean, soft cloth or optical tissue (e.g., Kimwipes).
6. Gently rub at the remaining salt from the abraded area with about five passes of a soft, clean cloth or optical tissue soaked in 50-50 isopropanol-distilled water.
7. Quickly and gently rub dry the abraded area with a soft, clean cloth or an optical tissue.

4.4 EDGE ATTACHMENT FLEXURE BEAM

The flexure beam test specimens shall be representative of the transparency cross-section and edge construction. Figure 4.4.1 presents a sample drawing of a typical 3"x15" three-point or four-point loaded beam. The test beams shall be mounted in a fixture which closely simulates edge fixity of the actual production structure. It is recommended that specimens be tested to the critical combined loading condition during bird impact at a

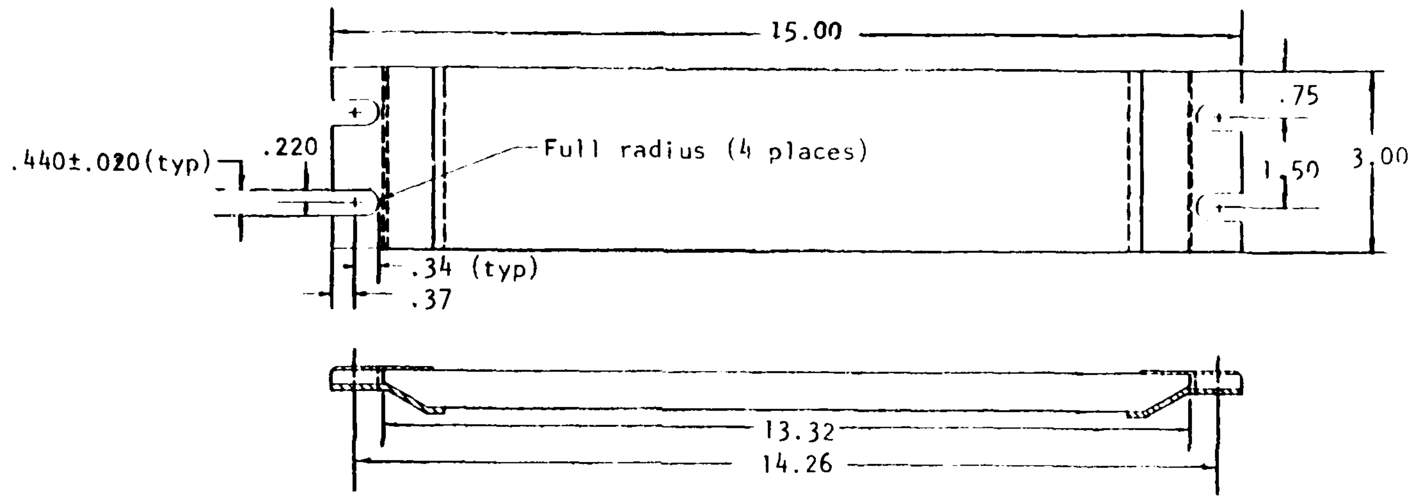


Figure 4.4.1. Typical Edge Attachment Beam.

displacement rate of 2,000 inches per minute using the high performance, electrohydraulic closed-loop (MTS) procedure described under paragraph 4.2.

For all tests, load versus displacement data should be stored in the digital memory of a transient recorder and played back at reduced speed on an X-Y recorder. High speed motion pictures could also be obtained. Information on edge response, fracture, and energy absorption provided by edge attachment screening tests can define design deficiencies of candidate configurations and allow for corrective action prior to production commitment.

4.5 AIR CANNON TEST

Plate specimens for air cannon testing shall be bandsawed to 12x12 inch, no finish-machining being required. It is recommended that a ballistic range be set up to use a one-inch diameter steel sphere projectile launched by an air cannon. Provide free-edge mounting by taping each plate to a picture frame support using doublesided tape. Utilize the appropriate instrumentation needed to measure and record impact velocity.

4.6 RAIN EROSION TEST

Rain impingement tests at 500mph on test specimens inclined at 30° to the direction of motion will be conducted by the Government on the rotating arm apparatus at Wright-Patterson Air Force Base. This rotating arm apparatus consists of an eight-foot diameter double arm blade. It is designed to produce high tip velocities with negative lift and a low drag coefficient. Mated test specimens are mounted at the leading edge tip sections of the double rotating arm. The test specimens can be subjected to variable speeds of 0 to 900 mph. The double arm is mounted

horizontally on a vertical drive shaft (see Figure 4.6.1). Simulated rainfall is produced by four curved manifold quadrants. Each manifold quadrant has 24 equally-spaced capillaries. Raindrop size and drop rate are controlled by the capillary orifice diameter and the head pressure of the water supply. The manifold quadrants are mounted above the tips of the double rotating arm. Raindrops from the simulation apparatus impact the test specimens throughout their entire annular path. Rain droplets are 2.0 mm diameter and generated at the rate of one inch/hour of simulated rainfall.

At test intervals of 1, 2, and 5 minutes, all specimens will be examined with a high resolution scanning electron microscope and the percentage of coating removal recorded.

4.7 MODIFIED FLATWISE TENSION TEST

Using ASTM D952 or ASTM F521-77 as a guideline, specimens are machined to the 2z2-inch recommended size with suitable equipment such as an end mill. The specimen test area is undercut to a 1 1/8-inch diameter (1.0 sq. in. test area) as shown in Figure 4.7.1 to ensure failure in the test interlayer, and to minimize specimen-to-fixture bondline failure. Specimens are bonded to two-inch square loading blocks using room temperature curing adhesive; an alignment fixture being used to center the specimen and align the loading blocks to ensure a true tensile test. Tests are conducted at a loading rate of 100 lb/sec in an electrohydraulic closed loop test machine; load versus displacement data being recorded.

4.8 MODIFIED TORSIONAL SHEAR TEST

Using ASTM D229 as a guideline, machine specimens to the configuration shown in Figure 4.8.1, having an annular test area of .392 sq. in. The nature of this test is to apply a

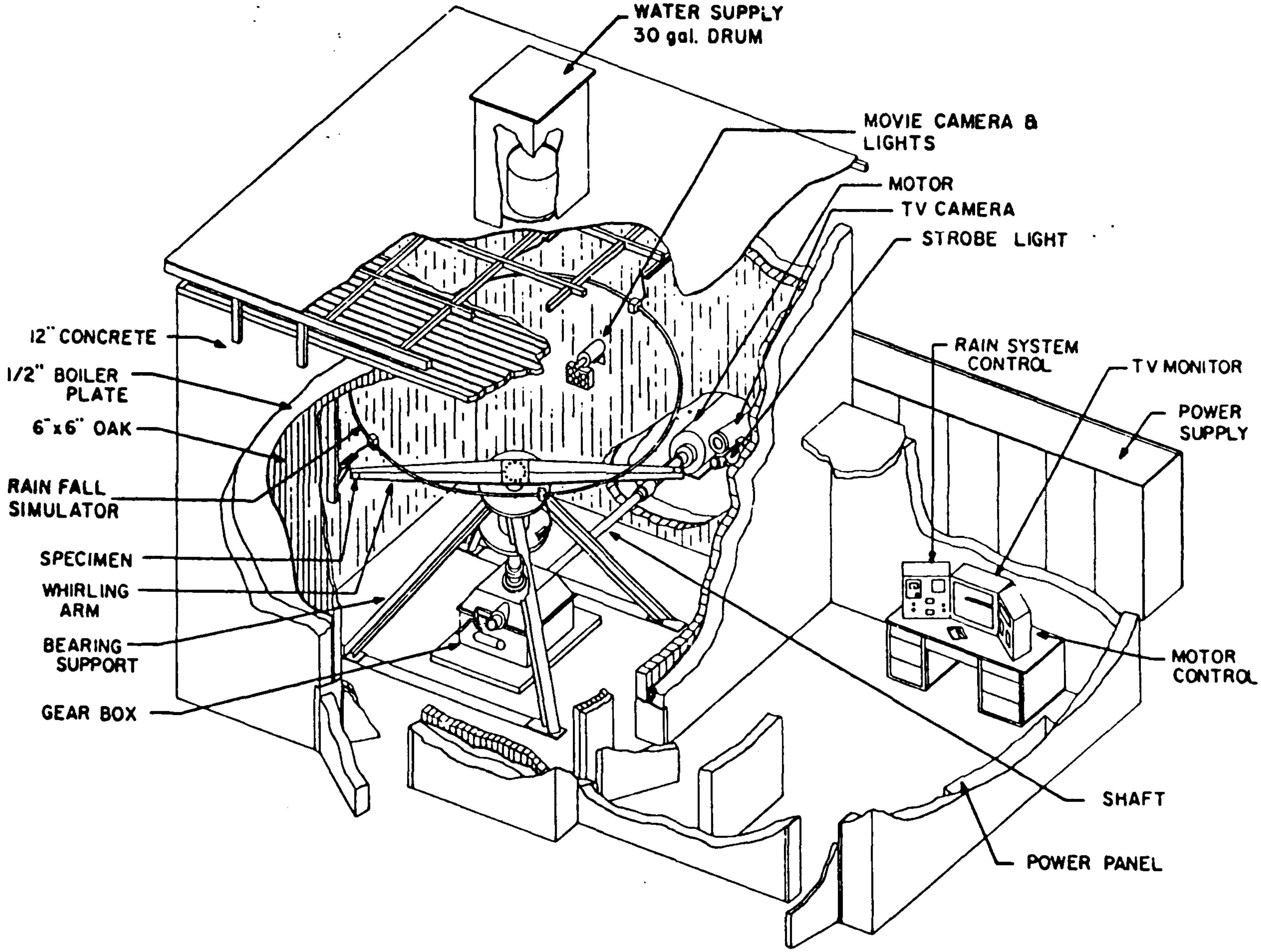
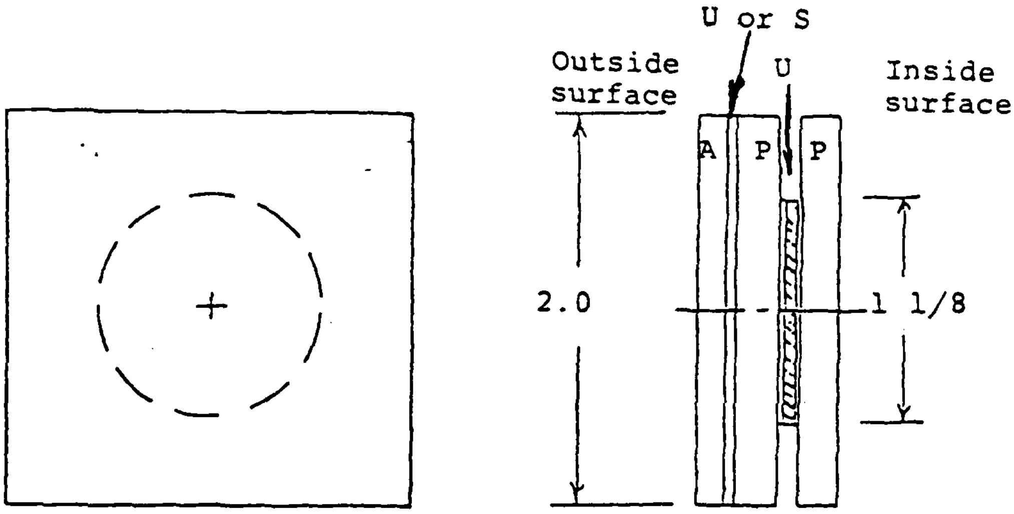


Figure 4.6.1. Mach 1.2 Rain Erosion Test Apparatus.



A = Acrylic
P = Polycarbonate
S = Silicone
U = Urethane

- Tested Interlayer (Not to Scale)

Figure 4.7.1. Modified Flatwise Tension Specimen.

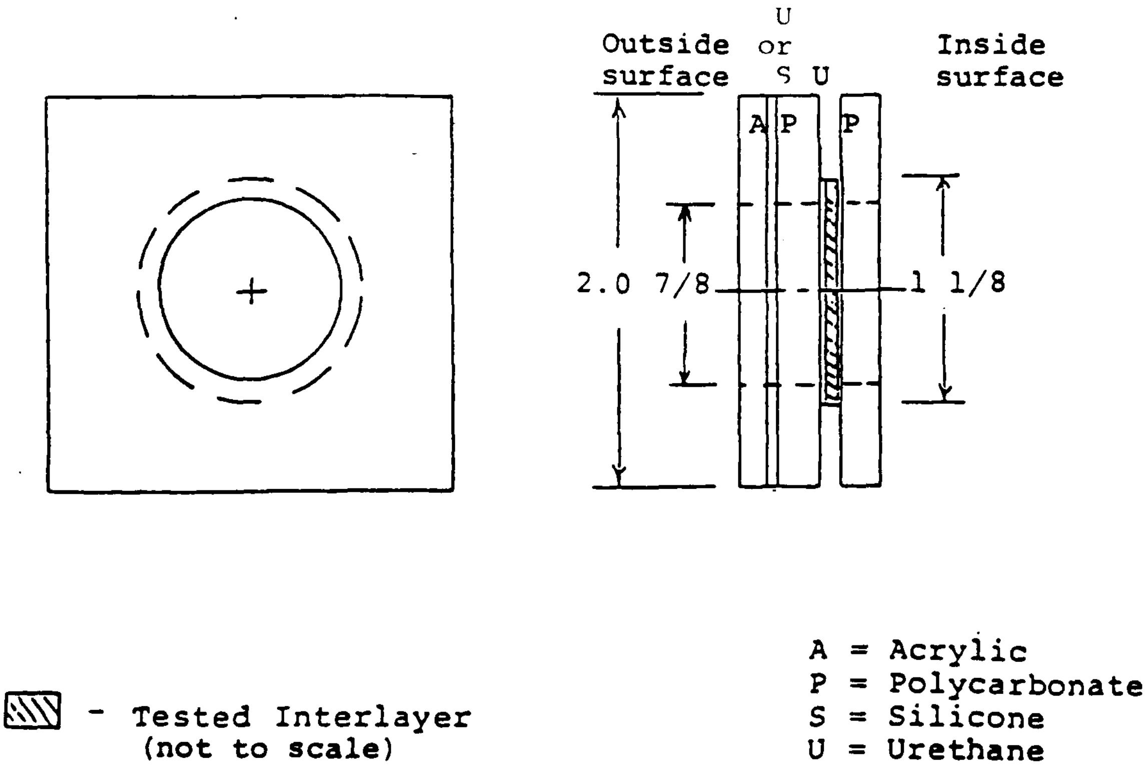


Figure 4.8.1. Modified Torsional Shear Specimen.

peripherally uniform strain distribution which varies linearly with the radius. A nonlinear material such as an interlayer results in a nonlinear radial stress distribution which yields an apparent shear strength which may differ from the actual. The nonlinear effects of a material on the test results can be reduced by forcing the inside radius to approach the outside radius--practical design considerations make this impossible to achieve. The specimen design has been sized to minimize the nonlinear effects while maintaining consistent and reliable test results.

Torsional shear tests are conducted at an angular displacement rate of 10 degrees/minute, which results in an equivalent average linear shear displacement rate (equivalent average linear shear displacement rate = average angular displacement rate x (π/360) x (r_i+r_o)) of 0.087 in/min. Specimens are tested by holding one surface ply stationary with an aluminum fixturing socket attached to the closed loop MTS system load cell and applying a torque to the other ply through a fixturing socket attached to the actuator.

4.9 MODIFIED WEDGE PEEL TEST

Using ASTM D3762-79 as a guideline, machine wedge peel specimens and wedge to the configuration shown in Figure 4.9.1, fabricated to the 1x10-inch size. A 1/8-inch wide slot, centered on the interlayer to be tested, is machined 1-3/16 inches into the end of each specimen. The specimens and aluminum wedges are sized to expand the stress gradient for various points of delamination so as to maximize the differences in the delamination lengths of the various materials.

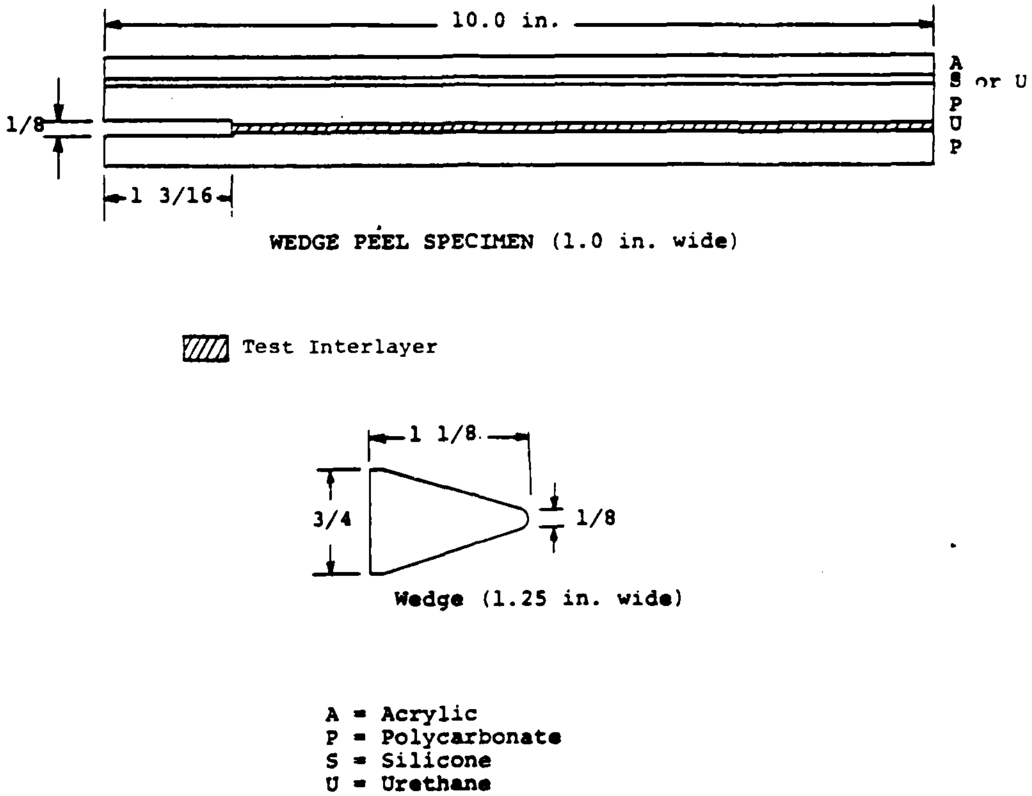


Figure 4.9.1. Modified Wedge Peel Specimen and Wedge Configuration.

Wedge peel tests are conducted by inserting the wedge into the specimen slot, thereby causing delamination of the specimen along the interlayer of interest. The wedges are inserted flush with the edge of the specimen. A fixture holds the wedges in position for the duration of the test. The delamination length is measured at time intervals of 0.1, 1, 2, 4, 7, 12, 24, 48, 72, and 100 hours after insertion of the wedge.